Nulling Interferometry

SPIE

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Gene Serabyn
JPL

Planet Detection

- **Indirect Methods** (= perturbations to stellar parameters):
  - Stellar Position → Astrometry
  - Stellar Velocity → Radial Doppler Shifts
  - Stellar Intensity → Transits, Microlensing
- **Direct Methods** (= direct detection of planetary radiation)
  - Direct Imaging → Very Large Telescopes
  - Starlight Suppresion → Coronagraphy, Nulling Interferometry

Comparison of direct approaches

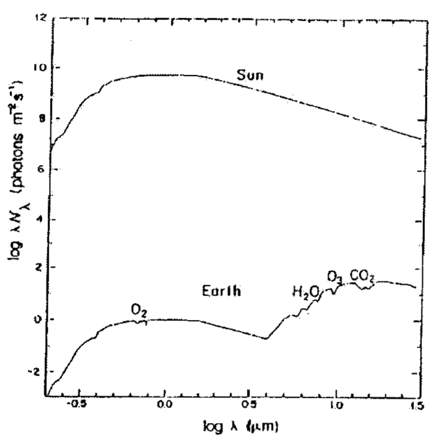
- 1 AU ⇔ 1.0 arcsec at 1 pc
  0.1 arcsec at 10 pc
- 10-m aperture at $\lambda = 10\ \mu m$ has $\lambda/D = 200$ mas

- **To see an exact Earth-analog at 1 AU from its star:**
  Nulling Interferometry: $\theta < \lambda/D$ (< few 0.1 arcsec)
  stellar distance ≈ 10 pc
  Coronagraphy: $\theta > 5\ \lambda/D$ (> 1-2 arcsec)
  stellar distance ≈ 1 pc
  Direct imaging: $\theta > 10 - 30\ \lambda/D$
  telescope diameter > 20 m
- With 10 m or smaller apertures, only nulling interferometry can observe sufficiently close to large numbers of nearby stars in the mid-infrared, where the contrast is reduced.

Optimal waveband for direct planet detection

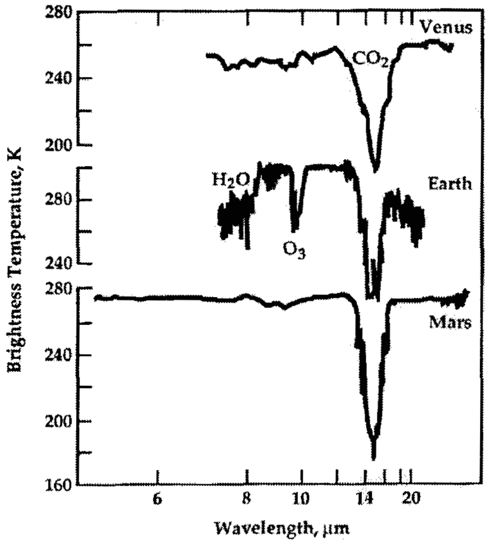
- **Visible Light:**
  Reflected Stellar Flux
  Contrast = $10^9 - 10^{10}$

- **Thermal Infrared:**
  Thermal Planetary Emission
  Contrast = $10^6 - 10^7$



Mid-infrared Spectroscopy

- Search for an atmosphere: CO_2
- Search for water
- Search for life (O_3 in lieu of O_2)



Comparison of MIR Flux Levels

Distance = 10 pc Wavelength = 10 µm

- Signal strengths:

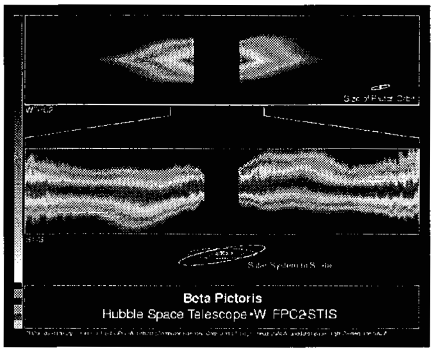
G2 star	2.2 Jy
Exozodiacal emission	200 µJy
Jupiter	2 µJy
Earth	0.3 µJy

- **Solar-level exozodiacal emission is much brighter than planetary emission**
- Backgrounds:

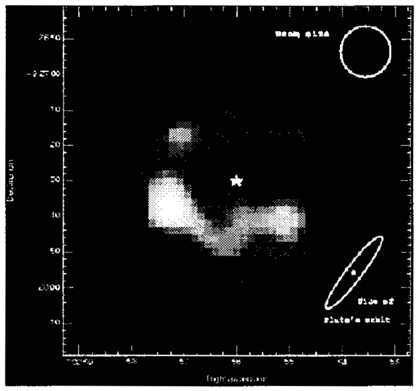
Zodiacal emission	800 µJy
Sky (emissivity = 0.1)	30 Jy

Dust Disks around Nearby Stars

Visible Wavelengths

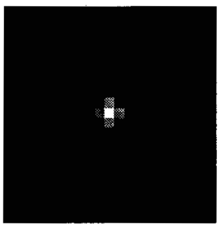


Submillimeter

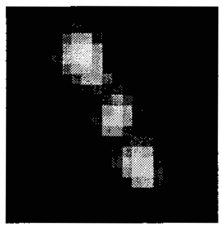


- Both images show dust primarily at > 30 AU
- Cold dust at Kuiper-belt-like radii
- IRAS: 15% of nearby MS stars show cold dust (to limit of 100 zodi)

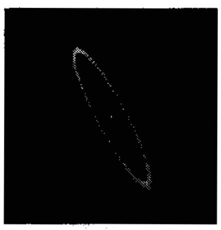
HR 4796



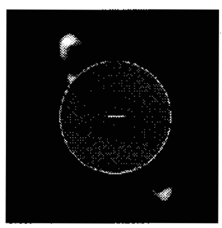
12.5 μm



24.5 μm



Computer Model



HST/NICMOS

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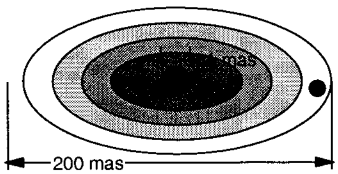
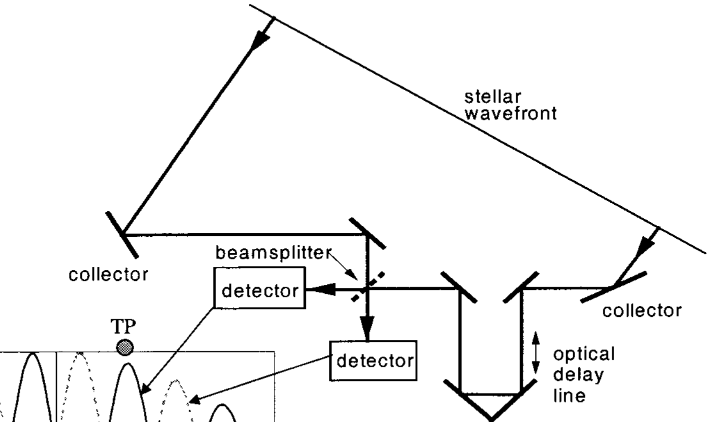
Nulling Roadmap

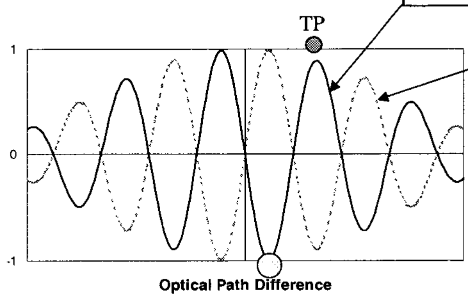


Target at 10 pc

- **Keck:** Characterize exozodiacal MIR emission around nearby stars.
  - Our 10 μm integrated zodiacal flux =
    10^{-4} of solar flux
    10^{-6} of thermal sky background
  - ⇒ Null star **and** remove background.
- **SIM:** demonstrate optical nulling with nanometer-level control needed by TPF.
  - 10^{-6} null @ 10 μm ⇔ 10^{-4} null @ 1 μm
- **TPF:** detect planets at 10 μm in the presence of stellar, zodi, and exozodi fluxes
  - MIR (7-20 μm) null of 10^{-6}.

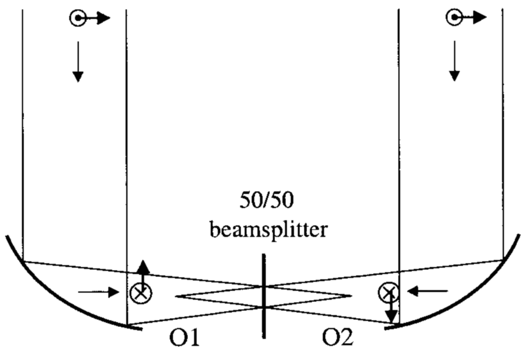
Nulling: Basic Concepts

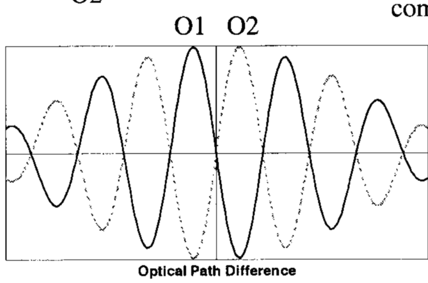




- Multiple collecting apertures
- Combine light interferometrically to put fringes on the sky
- Cancel on-axis starlight
- Transmit off-axis planetary light

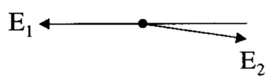
Original Nulling Concept





- Symmetric layout: at ZPD
  - ⇒ at ZPD equal (1/2) power to O1 & O2
  - ⇒ complementary fringes at O1 & O2
  - ⇒ no null at ZPD
- Best cancellation at finite OPD
  - ⇒ cancellation is chromatic
- 2 polarizations yield fringes out of phase by π
  - ⇒ fringe patterns cancel completely

General achromatic nulling requirements

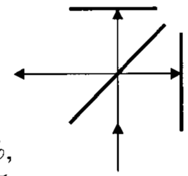


- Desire $E_1 - E_2 = 0$
- High degree of **symmetry** and **stability** required:
  - **E** fields in the two input beams oppositely oriented
  - Equal beam intensities
  - Zero relative path difference
  - Simultaneous zero of OPD for both polarizations
  - Simultaneous zero of OPD across aperture:
    - Surfaces typically limit null depth to ≈ 1- Strehl ratio, or few %
    - ⇒ wavefront cleanup with single mode spatial filter required
  - Simultaneous cancellation at all wavelengths in the passband
    - BW evolution: SIM 20%, Keck 30 - 50%, TPF 100 %
  - Small stellar angular diameter

Achromatic Destructive Interference

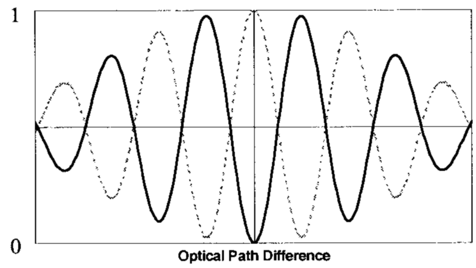
- Normal ``constructive'' 2-beam interferometer: $I_{out} = I_{in}(1+V\cos\varphi)/2$
- Bandwidth limitation to destructive interference minima:

$$\frac{I_{min}}{I_{max}} = \frac{1}{2}\left(1-\mathrm{sinc}\frac{\pi}{2}\frac{\Delta\lambda}{\lambda}\right)$$



- For bandwidths of 5, 10, 20, 30, 40, and 50%,
  the deepest cancellation is 0.05, 0.2, 0.8, 1.8, 3.2, and 5%.

- Deeper cancellation requires an achromatic approach, e.g. a relative field flip:

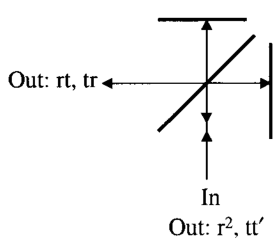


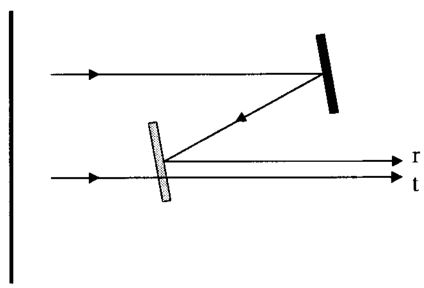
$$I_{out} = I_{in}(1-V\cos\varphi)/2$$

Electric Field Reversal

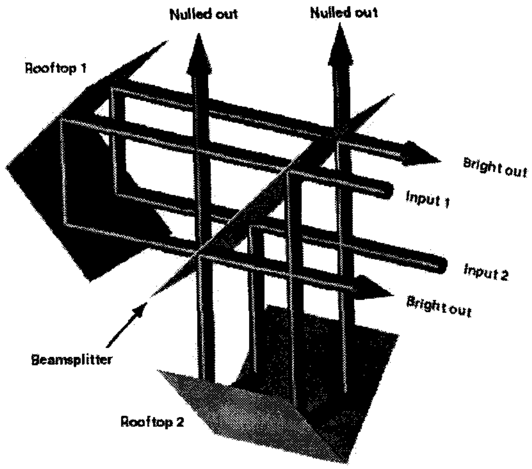
- **Achromatic field reversal can be effected by means of:**

- Geometric field flip: rotational shearing interferometer
- Through-focus field flip: (also RSI)
- Phase retardation: chromatic waveplate

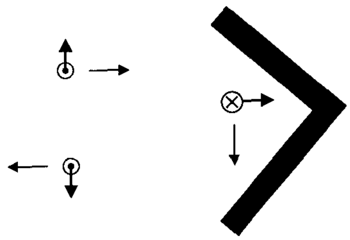




Beam Combination in a Rotational Shearing Interferometer

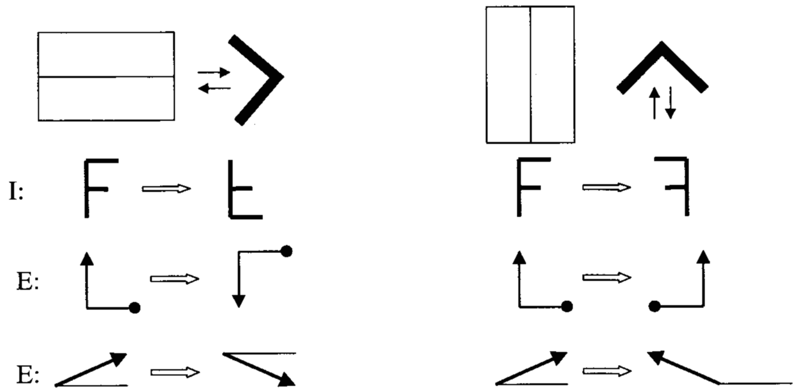


Rooftop Mirrors



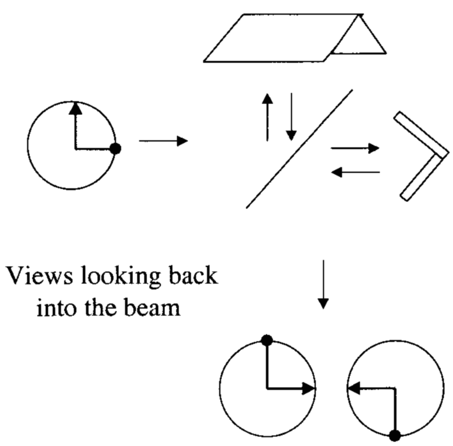
- Rooftop flips E-field component which is normal to roof line

Orthogonal Rooftop Mirrors

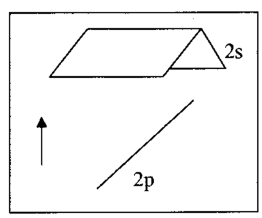


- Electric field vectors orthogonal to rooftop axis flipped by 180 degrees.
- Output beams have polarizations rotated 180 degrees w.r.t. each other.
- Output apertures are rotated 180 deg. w.r.t. each other.

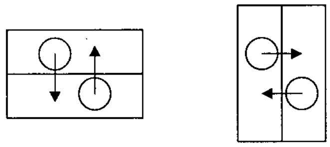
Polarization Compensation

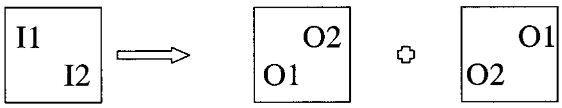


- Output images and electric fields rotated by 180 deg.
- Asymmetric: one arm has 2 s reflections, other has 2 p refl.
- Add fold mirror in each arm to symmetrize reflections:



Beam Combination in RSI

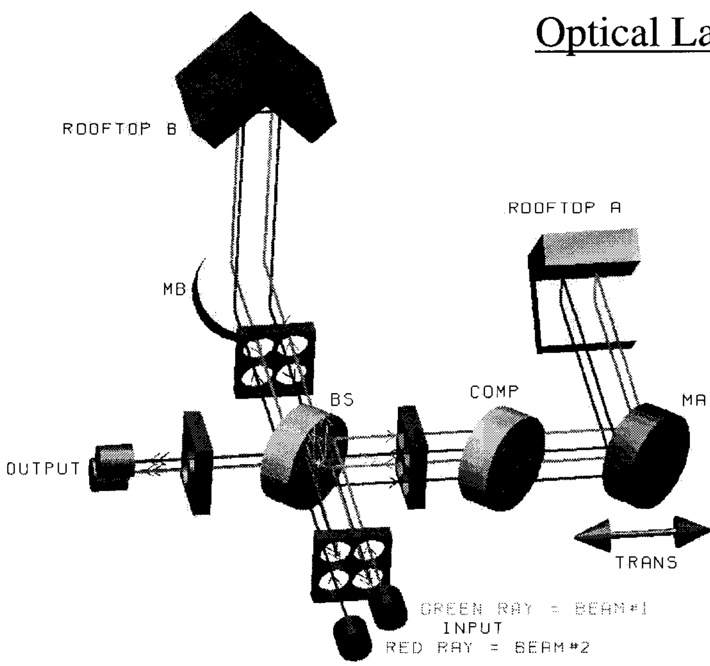




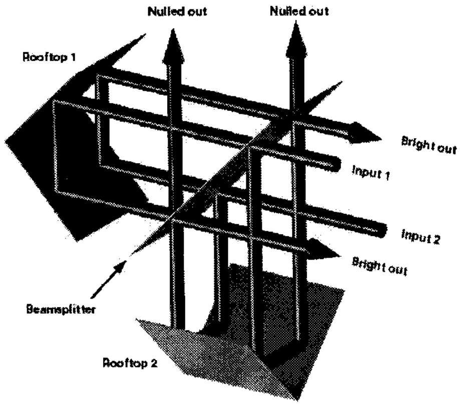
Inputs

Twin Outputs on either side of beamsplitter

Optical Layout



Implementation 1: rotational shearing interferometer



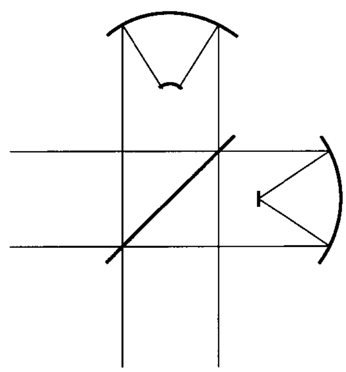
• **Advantages:**
- Relies solely on flat mirrors
- Achromatic, geometric π phase flip
- Phase flip separated from OPD
- Nearly perfect symmetry (with extra folds)
- Automatic power balance:
  Beamsplitter used in double-pass, so same RT product multiplies both inputs
- High R/T ratio tolerance at 2-pass b.s.
  (R near 0.5 only maximizes throughput)

• **Drawbacks:**
- High quality rooftop reflectors needed

• **Both:**
- 2 nulling outputs

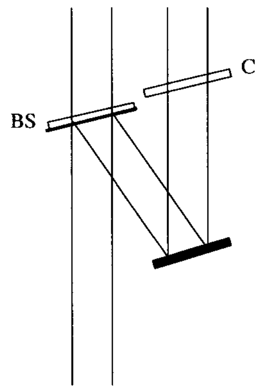
Implementation 2: Phase shift through focus

- Passing through focus inverts aperture, adds achromatic 180 degree phase shift.
- Replace rooftops by cat's eyes:
  - one secondary flat, at focus
  - other secondary curved, prior to focus
- **Advantages:**
  - Achromatic 180 degree phase flip
  - Phase flip separated from OPD
  - Relaxed b.s. R/T requirements
- **Disadvantages:**
  - Differing angles of incidence on secs.
  - Point focus on flat secondary
  - 2 nulled outputs



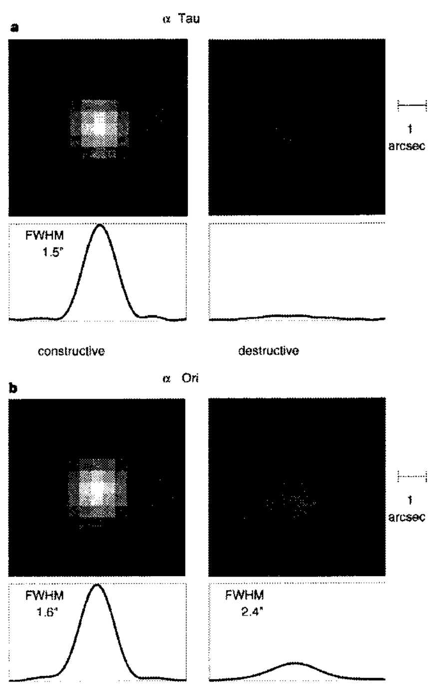
Implementation 3: dielectric waveplate

- 90 degree phase shift at b.s.
- Dielectric plate compensates for b.s. plate;
  adds another 90 degree phase shift.
- **Advantages:**
  - simple layout and components
  - no wavefront inversion
  - one nulling output
  - can use a second waveband to sense OPD
- **Challenges:**
  - Requires highly accurate coatings:
    single-pass beamsplitter requires nearly perfect R/T match for intensity balance
  - Requires highly accurate tailoring of compensator refractive indices across band.
  - Phase flip and OPD not independent.



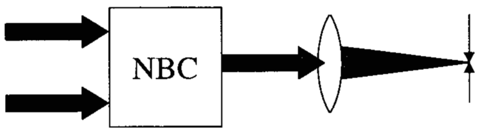
UofA MMT MIR nulling

- Waveplate scheme
- On telescope
- Cancelled 2 panels of MMT
- Rejection of 1/24 achieved
- No OPD control



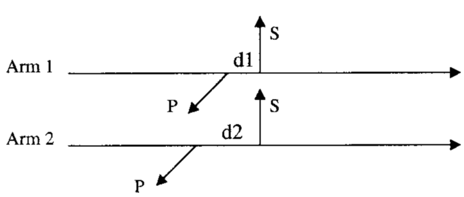
Wavefront Cleanup

- Aberrated wavefronts prohibit simultaneous field cancellation across the wavefront. N limited to about 1-S.
- Wavefront cleanup required for deep nulls
- Effected by means of a spatial filter in output focal plane
- Only the point-spread function core is transmitted
- Limits nulling to a single spatial mode of the telescope



Sources of null degradation

• Finite Stellar Diameter	Static
• Nonunity visibility:	
- Wavefront errors - removed by spatial filtering	Static
- Polarization rotation mismatch	Static
- Intensity mismatch: transmission asymmetries,	Static
pointing jitter induced scintillations	Fluctuating
• Nonzero phase:	
- Optical path jitter	Fluctuating
- Differential s-p polarization delay (d1-d2 below)	Static
• Dispersion	Static

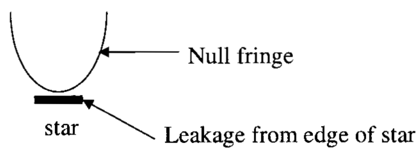


Null Depth Definition

- Null depth : $N \equiv I_{\min} / I_{\max}$
  where I_{out} and I_{in} are the nuller throughputs in the destructive and constructive states, respectively.
  $$N = (1 - V\cos\phi)/2.$$
- Both V<1 and $\phi \neq 0$ limit null depth and so drive the requirements.
- For V=1 and small phase errors $N = (\phi/2)^2 = (\pi x/\lambda)^2$
- For perfect phase matching $N = (1 - V)/2.$
- Examples:
  For $N = 10^{-4}$, $V = 0.9998$.
  For $N = 3 \times 10^{-5}$, $\lambda = 600$ nm, x = 1 nm
  For $N = 3 \times 10^{-5}$, $\lambda = 10$ μm, x = 17 nm

How deep is your null?

- Fundamental limit: Nonzero stellar diameter limits N to:
$$N = \frac{\pi^2}{16}\left(\frac{\theta_{dia}}{\lambda / b}\right)^2$$



- For a G2 star @10 pc, with an angular diameter of 0.93 mas, N=3e-5 at 0.63 μm requires a projected baseline of < 1.0 m.
- Note: A flux reduction by 10^{-4} corresponds to 10 magnitudes: On SIM, this leaves a flux of order 1000 photons/s/aperture.

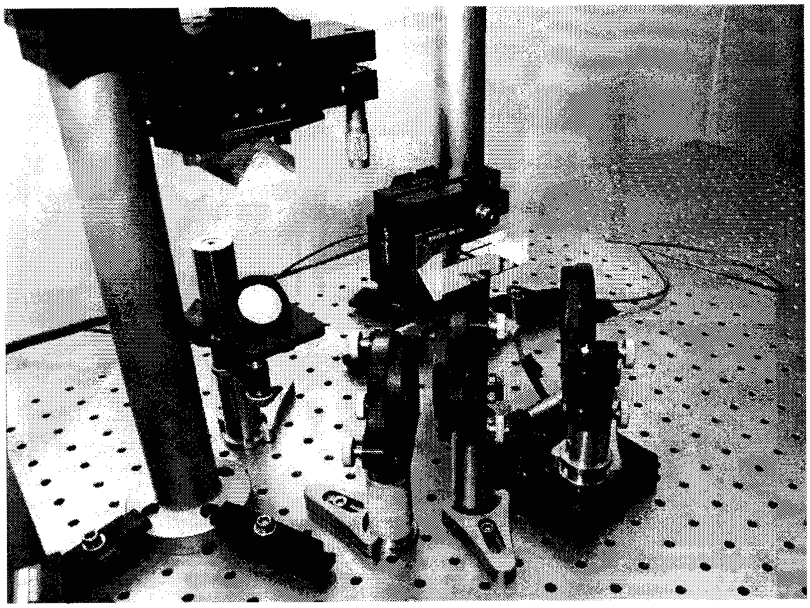
SIM requirements from null depth

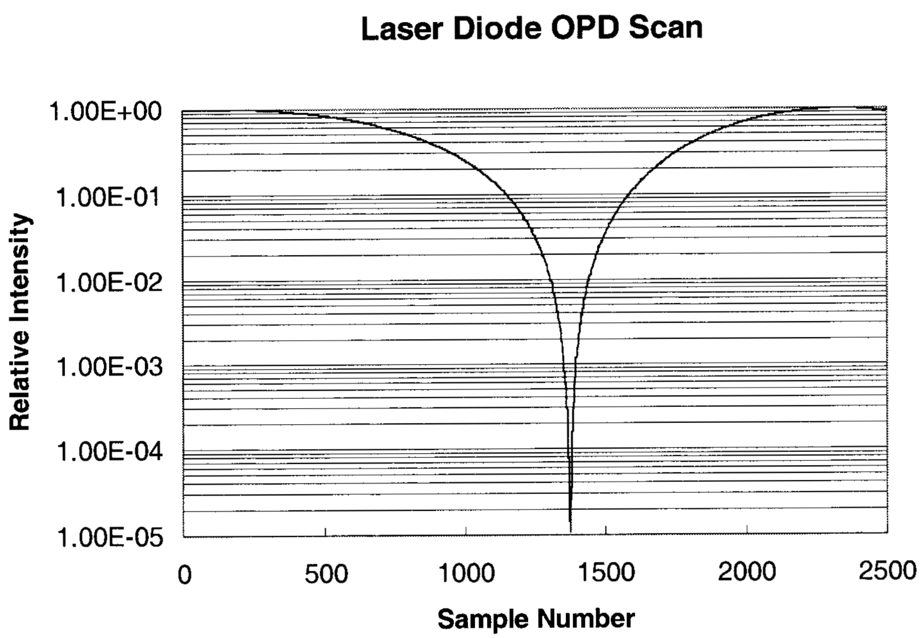
	Constraint	Null Contribution	Requirement	
Stellar Diameter Leakage	$\theta_{\mathrm{dia}} < 4\lambda\sqrt{N} / \pi b$	< 3e-5	b < 1.1 m	
Optical Path Errors	$x < \lambda\sqrt{N} / \pi\sqrt{1+\sqrt{2}}$	< 3e-5	< 0.8 nm	
Transmission Asymmetries	$\Delta I / \bar{I} < 4\sqrt{N}$	<1e-5	< 1.2 %	
Pointing Jitter	$\alpha < 0.8(\lambda/D)\sqrt[4]{N}$	<1e-5	25 mas	$\frac{1}{22}\frac{\lambda}{D}$
Differential Polz'n Rotation	$\phi < 2\sqrt{N}$	< 1e-5	< 0.36 deg.	
Differential s-p Polar. Delay	$\Delta < 4\sqrt{N}$	< 1e-5	< 0.72 deg.	

Keck requirements from null depth

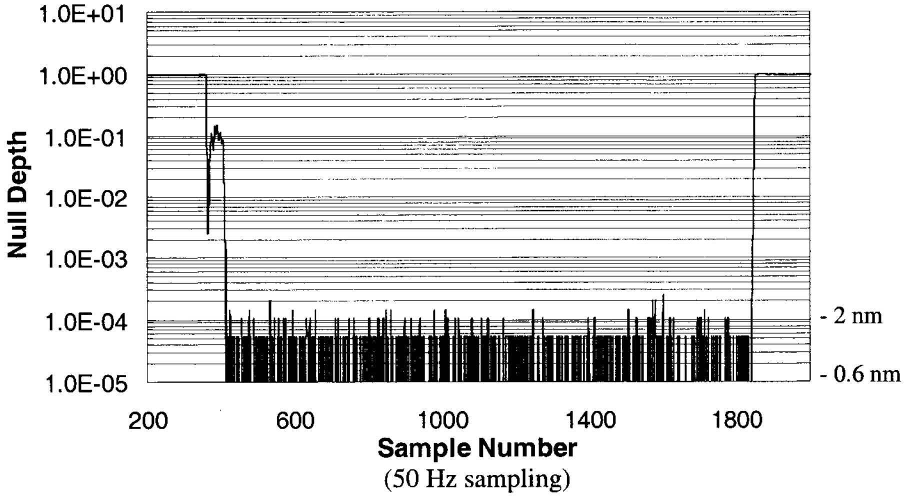
	Constraint	N=1e-4 Req.	N=1e-5 Goal	Impactee
Differential Image Rotation	$\theta < 2\sqrt{N}$	< 1.1	< 0.36	LDL
Throughput Asymmetries	$\frac{I_{diff}}{\bar{I}} < 4\sqrt{N}$	< 4%	< 1.2%	Coatings
Strehl Fluctuations (1-S)	$\frac{\sigma_I}{\bar{I}} < 2\sqrt{N}$	< 2%	< 0.6 %	AO
Optical Path Errors	$x < \frac{\lambda}{\pi}\sqrt{N}$	< 32 nm	< 10 nm	FDL
Feed Forward Time	$\frac{t_{ff}}{t_{02}} < \left(2\sqrt{N}\right)^{6/5}$	< 0.7 msec	< 0.18 msec	Frng Trckr
Differential s-p Polar. Delay	$\Delta < 4\sqrt{N}$	< 2.3	< 0.72	Coatings

Experimental Setup

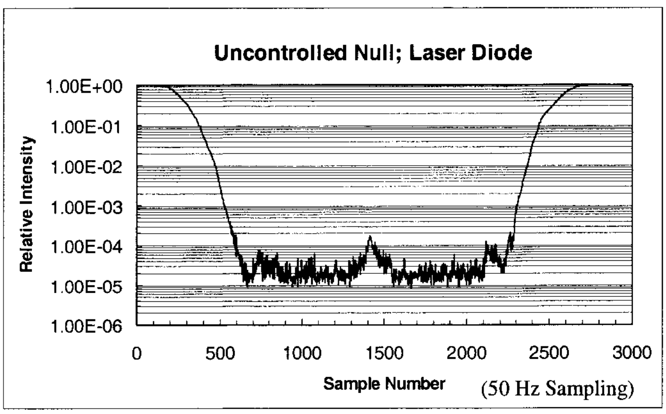




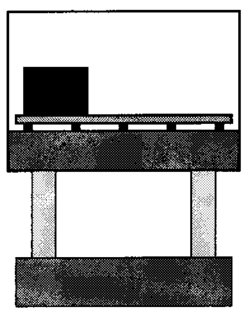
Dither-controlled Laser Null

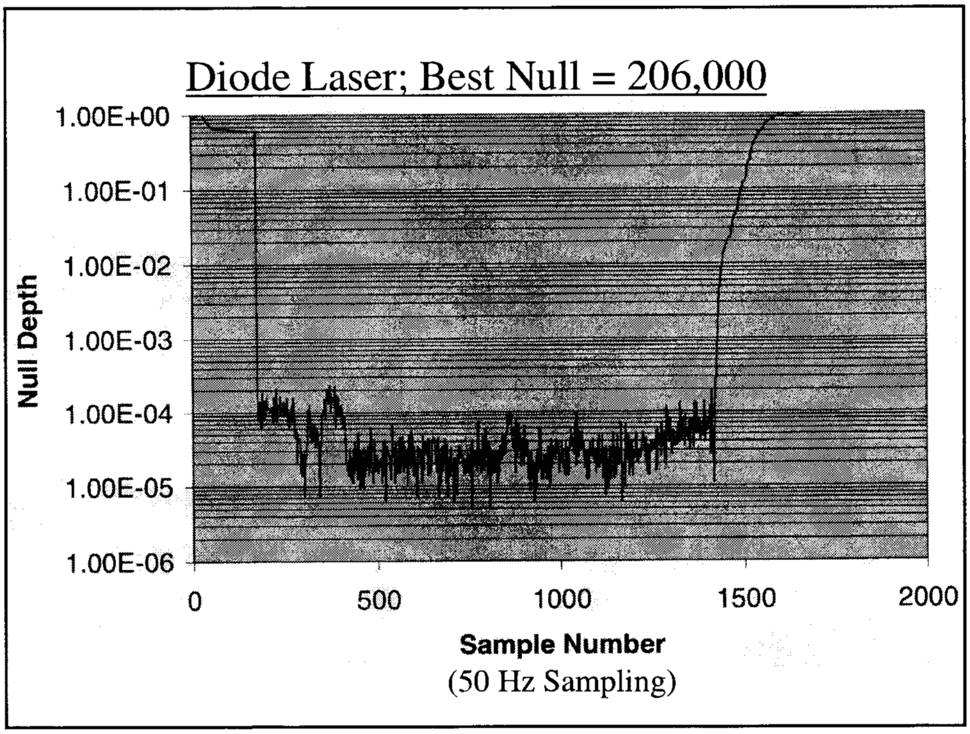


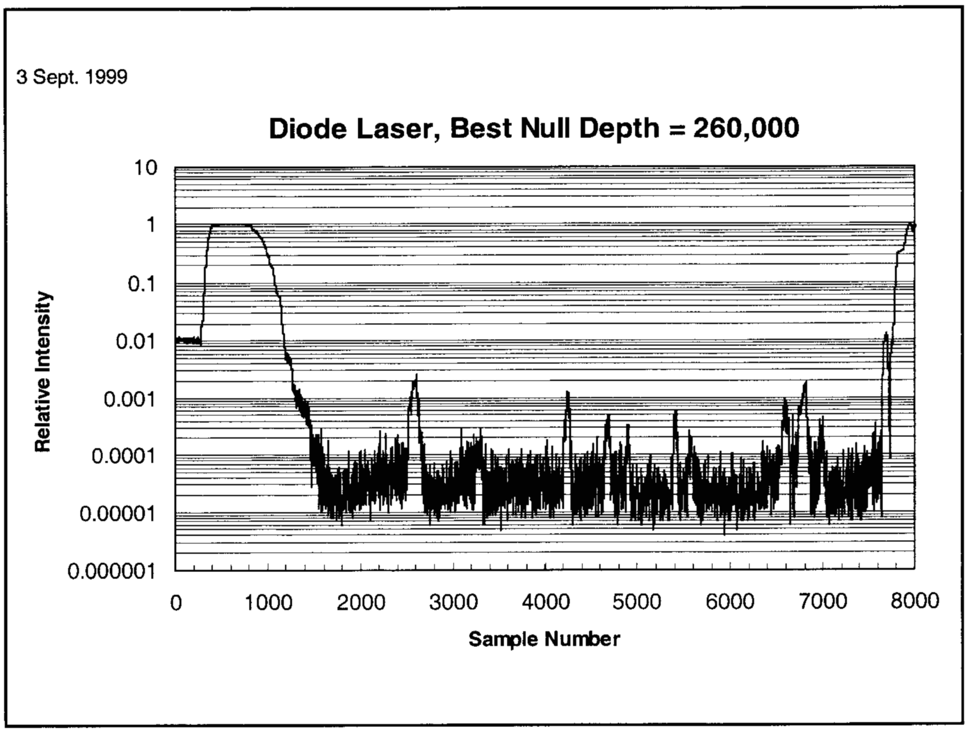
Environmental Improvements in New Lab:

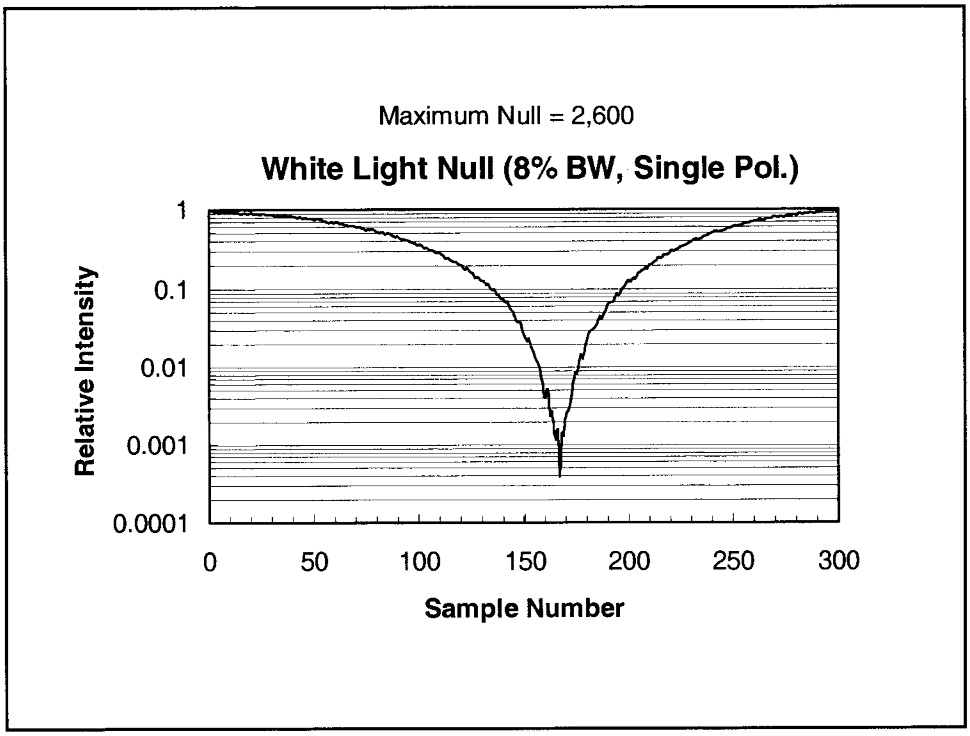


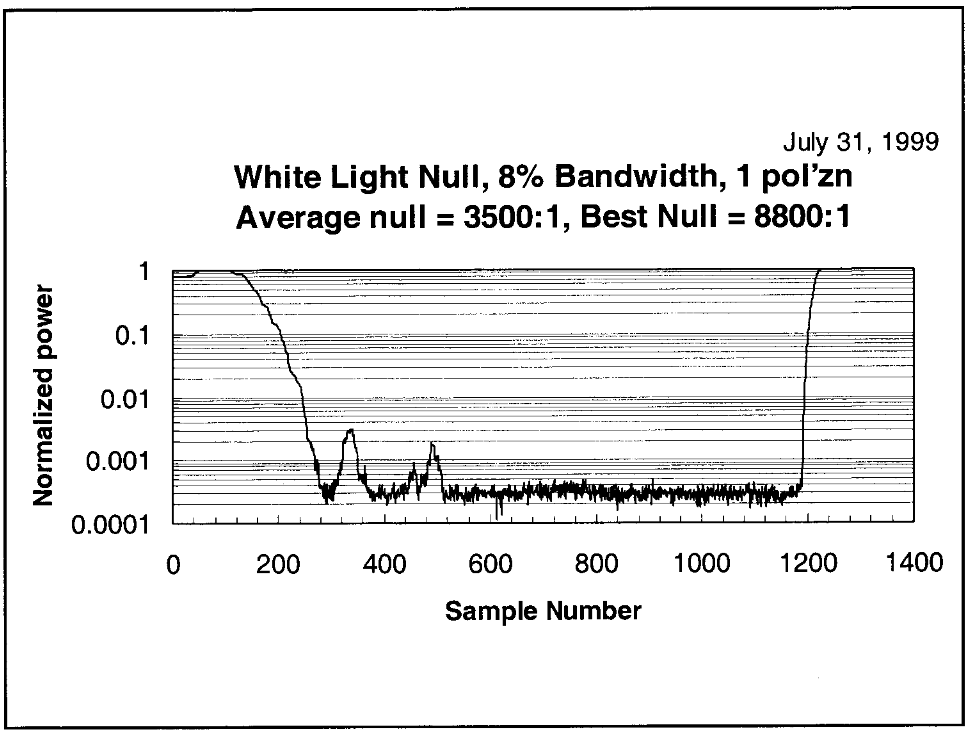
Vibration and Acoustic Isolation

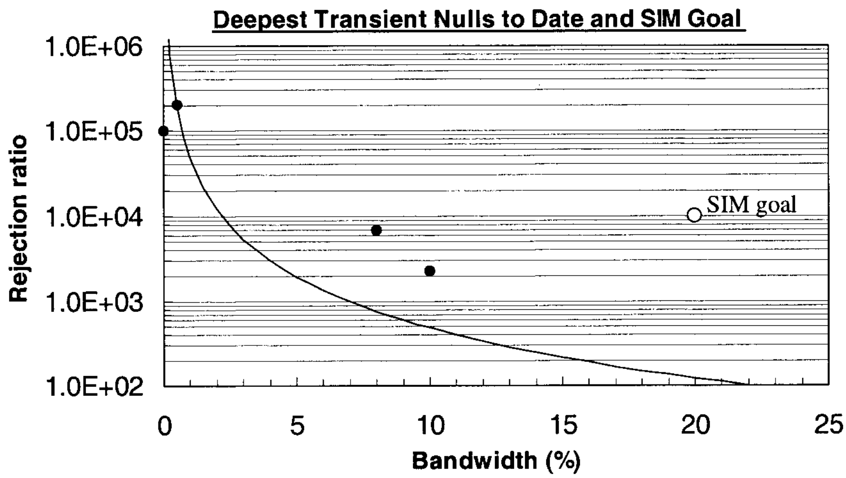



Diode Laser; Best Null = 206,000
Null Depth
1.00E+00
1.00E-01
1.00E-02
1.00E-03
1.00E-04
1.00E-05
1.00E-06
0
500
1000
1500
2000
Sample Number
(50 Hz Sampling)


3 Sept. 1999
Diode Laser, Best Null Depth = 260,000
Relative Intensity
10
1
0.1
0.01
0.001
0.0001
0.00001
0.000001
0
1000
2000
3000
4000
5000
6000
7000
8000
Sample Number


Maximum Null = 2,600
White Light Null (8% BW, Single Pol.)
Relative Intensity
1
0.1
0.01
0.001
0.0001
0
50
100
150
200
250
300
Sample Number


July 31, 1999
White Light Null, 8% Bandwidth, 1 pol'zn
Average null = 3500:1, Best Null = 8800:1
Normalized power
1
0.1
0.01
0.001
0.0001
0
200
400
600
800
1000
1200
1400
Sample Number



Sources of null degradation for wider bands

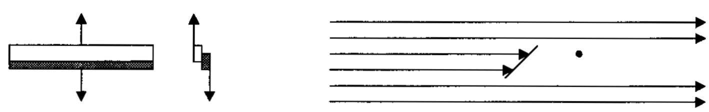
- Input lens decenter
- Input polarizer wedge angle
- Beamsplitter/compensator thickness or rotation mismatch
- Beamsplitter/AR coating phase shifts
- Unequal number of AR coating traversals (BS/Comp)
- Mirror protective coating asymmetry
- Extra reflections in filters, polarizers
- Intensity balance vs. wavelength

The Future: Control and Modulation Schemes

- Active Intensity Matching
- OPD Control:
  - Control one output by means of the second
  - Control one waveband by means of another
  - Control via metrology
- Signal Modulation Schemes:
  - Baseline rotation: fringes sweep across zodi/planet
  - Spatial chopping:
    nulling removes star; chop on/off zodi/planet
  - OPD fringe scan after multiple baseline nulling

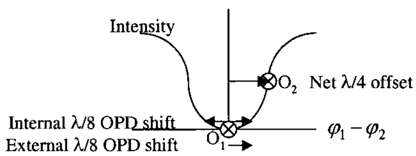
Intensity Matching

- Intensities in the two beams must be matched achromatically;
  - dielectric attenuators are excluded.
- Pointing and beam vignetting both affect intensity;
  - desirable to divorce pointing from intensity control (to the extent possible).
- Employ both beam vignetting and pointing to modify intensities:
  - Rooftop tilt actuator used for fine pointing/intensity control.
  - Modulate flux via rotating ``Venetian blind'' across aperture center.
  - Use variably shadowed obscuration, i.e., ``scissors''.



Optical OPD control

- **Approach:** The nuller has 2 outputs. Use 1 output to control the 2nd.
- **How?**
  - An *internal* nuller path delay causes the two nuller outputs to depart from null in opposite directions (opposite relative phases):
    Output 1 has E_1 ahead of E_2; output 2 has E_2 ahead of E_1.
  - An *external* path delay (i.e., prior to the nulling combiner) *always* advances one beam relative to the other.
- ∴ The 2 types of offsets can be combined to leave one nuller output on null, and the second output at an OPD offset of λ/4.
- At the quadrature output, a large signal and a linear intensity-OPD relation are available for control. Control sensitivity at half-power output:



$$\frac{\Delta I}{I} = 2\pi \frac{\Delta x_{OPD}}{\lambda}$$

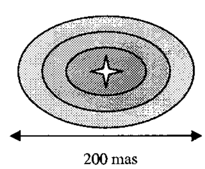
or ≈ 1%/nm

Keck Nulling Science Objectives

- Non-stellar MIR emission from nearby solar systems likely to be dominated by thermal exozodiacal emission from dusty disks, making planetary thermal emission difficult to detect.
- Prior to TPF, first probe exozodiacal flux levels around nearby stars with Keck-Keck single-baseline interferometry.
- Zodiacal/Stellar flux ratio @ 10 microns for our sun ≈ 1e-4.
- The 85 m K1-K2 baseline can characterize exozodi emission on sub-AU scales.

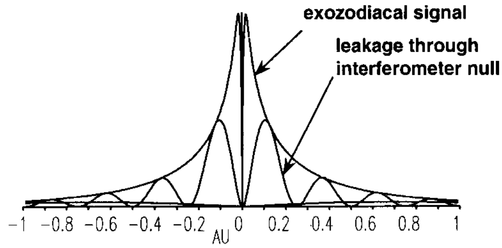
Angular sizes:

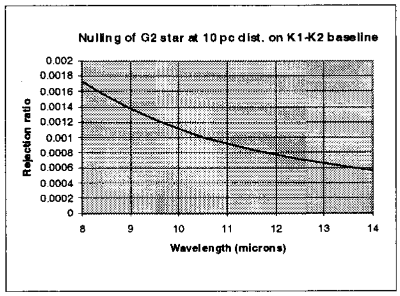
G-star diameter at 10 pc:	1 mas
1 AU at 10 pc:	100 mas
K1-K2 10 mu fringe spacing:	24 mas
Keck 10 mu beam diameter:	200 mas

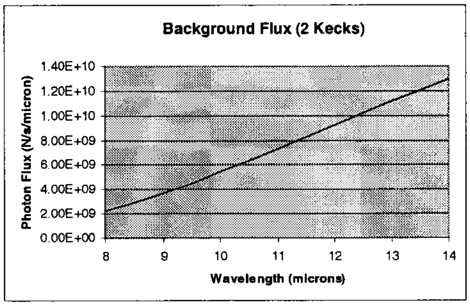


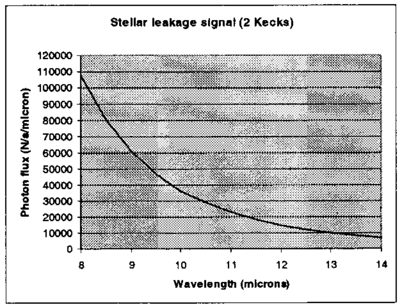
- Requirement: detection capability at the 10-solar-zodi equivalent
- Goal: 1-solar-zodi equivalent

Signals: I

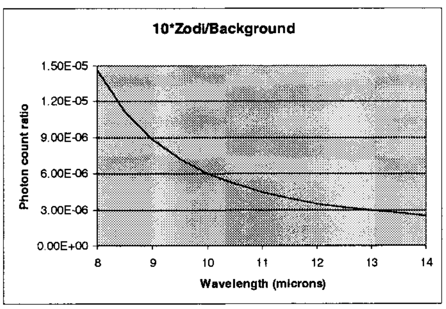


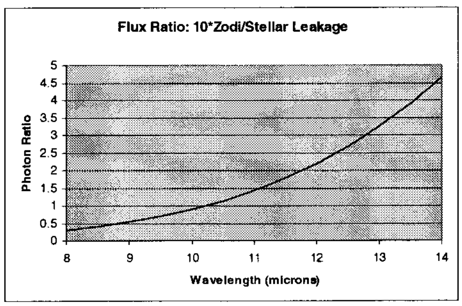


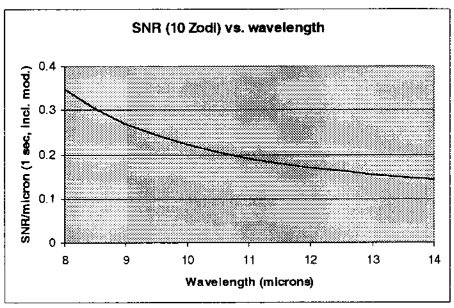




Signals: II







SNR for exozodiacal signal at Keck

- Pessimistic case: $\lambda = 10\ \mu m$, $\Delta\lambda/\lambda = 0.3$, emissivity = 0.65, total system efficiency = 0.046, cold throughput = 0.14, $A\Omega = \lambda^2$, 9 m diameter

- **Detection rates:**
- G star at 10 pc (2 Kecks) = 9e7 photons/s
- Stellar leakage thru null = 9e4 photons/s
- 10 solar zodis (2 Kecks) = 8e4 photons/s
- Background (2 Kecks) = 1.8e10 photons/s
- Noise (1 sec) = 1.35e5 photons
- SNR (1 sec; 10 solar Zodi; including modulation) = 0.2
- SNR (4 hr; 10 solar Zodi; including modulation) = 25

Future Work

- Broaden Bandwidth
- Move into Mid-Infrared (Cryogenic)
- Dual-polarization Nulling
- White-light Null stabilization
- Efficiency optimization
- Control architectures
- Component development (rooftops, beamsplitters, single-mode filters, AR coatings, etc.)
- Null at high altitude
- Null in space